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MECHANICS OF THE EXPLOSION BULGE TEST*

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*This paper was written while the author was employed at the Naval Research Laboratory, Washington, D. C. The opinions or assertions contained herein are the private ones of the writer and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

MECHANICS OF THE BULGE

INTRODUCTION

The need for a semi-works-scale test of weldments featuring simple geometry and controlled loading led to the adoption of bulge-test methods. Both tube and bulge tests permit controlled biaxial loading: tubes require axial tension applied concomitantly with internal hydrostatic pressure and bulges require fluid or gas pressure on edge supported diaphrams. Although the tube test has the advantage of providing uniform strain over a relatively extensive test area, massive equipment ' d elaborate gripping devices are required to avoid end-bending effects.[1] Consequently, tube tests are extremely expensive and have been limited primarily to fundamental research in the field of applied mechanics. The advantages of bulge tests, on the other hand, lie in the simplicity of equipment and experimental techniques. The principle disadvantage is the relatively small area of pole region which may be classed as being effectively under uniform strain. Bulges in sheet metal are produced by hydraulic pressure applied to a test diaphram clamped over a circular or elliptical opening. The extension of hydraulic bulge testing to full thicknesses of ship plate was accomplished by the detonation of an explosive suspended in air over the test plate. The explosive is used only as an expedient method for obtaining the large force necessary to develop a bulge in thick plate. The object-

ive of bulge testing welds in full thicknesses of ship plate is to provide semi-works-scale structural tests incorporating uniform and controlled loading of weld, HAZ, and parent plate and to thereby determine the factors controlling weldment performance.

Initial studies of flow[2] and fracture[3] in welded bulges have established the merits and usefulness of the test method. Study of the distribution of plastic strain in various weld and base-metal combinations was bade by measuring the distortion of a 20-line-to-the inch grid applied to the surface of the test plate by the photogrid process. Measurements showed that the stress and strain state imposed by the loading conditions are not always accepted by the weld joint. Depending upon the relative flow strengths of weld and base metal, a system of stress and strain entirely foreign to the remainder of the structure may be developed in the weld and near-weld regions. A study of the fracture characteristics of various weld and base-metal combinations indicated a wide range of performance which appeared to be determined by the properties of the deposited weld metal rather than the HAZ. Tests have been conducted at temperatures ranging from approximately -100° to +200°F. Results indicated that the explosion bulge tests is primarily an evaluation of the crack initiation stage of weldment failure (catastrophic failure of welded structures may be considered to occur in two stages -- crack initiation and crack propagation). Inasmuch as external mechanical notches are absent and the stress conditions of the bulge are essentially biaxial, extensive deformation is developed in

most weldments at ordinary temperatures of services (32°F and above) prior to the initiation of the fracture. Such data are applicable to the case of service entailing extensive deformation (explosion, collision, etc). Data significant to structures which operate at elastic loads are obtained by causing fracture to occur at near-zero levels of deformation. This is achieved by lowering the temperature, thus introducing a resistance to flow such as is obtained under conditions of severe tri-axiality. The requirements of low temperature to initiate failure in tough welds at low levels of deformation results in extensive fracturing of the base plate since most structural materials have an inherently low resistance to crack propagation at the sub-zero temperatures necessary for crack initiation. Crack initiation at a near-zero level of strain was found to occur at widely different temperatures depending upon the notch toughness of the test weld. Temperature thus serves as a basis of evaluation--the weld requiring the lowest temperature to initiate fracture is deemed most desirable.

Information obtained from bulge tests of sheet metal[4] provided a guide in establishing the present technique; however, the novel application to heavy plate and to welds involving differential straining in the various components of the weld zone posed new problems which required detailed study of the mechanics of test. As straining progresses in the hydraulic bulging of sheet metals, the magnitude of the strain at any given level of deformation varies from zero at the clamped edge to a maximum at the apex of the bulge. The extent of the pole region over

which the strains are substantially uniform is determined by the thickness-to-diameter (span) ratio and the degree of deformation to which the bulge is subjected. At a certain critical level of deformation, a condition of instability develops[5]. When unstable flow occurs, straining becomes localized, the geometry of the test specimen changes and the state of stress in that portion of the specimen undergoing plastic flow is no longer under control. In the hydraulic bulging of circular diaphrams, instability is identified by an increase in deformation with no increase in pressure. In the formation of an elliptical bulge the strain ratio at the crown of the bulge changes continuously, gradually approaching one. Thus, in the elliptical bulge the limiting condition is determined by that stage of deformation at which there is an excessive alteration in the strain ratio; i.e., a loss of control over the stress state. The following report is concerned with the mechanics of flow in the bulging of plate, particularly the effect of progressive straining (by multiple shots) in producing instability and localization of flow.

BULGING BY MEANS OF EXPLOSIVES

The extension of hydraulic bulge testing techniques to full thicknesses of ship plate was accomplished by the detonation of an explosive suspended in air over the test plate Fig. (1). The test plate was supported by a 3" thick armor saddle containing either a circular (r = 6") or an elliptical (a = 7.5", b = 4.8) opening (fig. 1a). To develop approximately uniform loading over the entire unsupported area of the test plate, the explosive was shaped to the form of a wafer of the same

-4-

configuration as the opening in the saddle plate (a = 6.5", b = 3.8" for elliptical charges and r = 5" for circular charges). The explosive was fired in air at a distance of 12 to 24 inches from the test plate; the standoff was regulated and the charge positioned by the simple expediency of a pasteboard carton cut to the desired height and marked for location of the charge on one end. The air blast was deemed to produce a uniformly distributed pressure wave normal to the plate surface. In that the unsupported area of the 20 x 20 inch test plate was only 28% of the total area, the high pressure applied to the supported portions of the plate effectively clamped the edges to the saddle (fig. 2).

The explosive is used simply as a means of obtaining the high forces required to develop bulges in thick plate. The depth of bulge produced by various combinations of weight and standoff of explosive are indicated by the empirical relationship of Figure (3). Good reproducibility of test conditions are demonstrated. The use of applied energy (wgt. of explosive, number of shots, etc.) as the criterion of performance gives an integrated "order of merit" which is difficult to resolve into engineering parameters; whereas measurements of either the biaxial strains developed in the surface of the bulge or reduction of thickness provide data of direct engineering significance. Consider, for example, the hypothetical case of two yields of the same terminal ductility but of different flow strength; while both welds will fracture at the same level of strain, the weld with the higher flow strength requires greater energy to develop the fracture strain. By separate observations

of "restraint to flow" and "flow at fracture" it is possible to break down the energy value into two parameters of engineering significance.

Figure 4 illustrates the restraining effect of an E12016 weld deposit in high-tensile steel - 3 shots (4 lbs. at 15") were required to produce the same general level of deformation as 2 shots against an E6010-HTS weldment. Likewise, a marked difference in resistance to flow is demonstrated between different types of structural materials; for example, 2 shots against the E6010 weld in mild steel developed almost twice the deformation produced by 2 shots against E6010 in HTS. Thus, the energy required to produce similar amounts of bulge (strain) varies greatly depending on the stiffness of the plate of weldment. In keeping with the principle that the explosive is used only as a means of obtaining the high forces required to bulge thick plate, a fixed wgt. of charge and standoff are selected for each series of tests according to the requirements of the material being bulged. In bulging 3/4" thick weldments of mild and high-tensile steel, a standard condition of 4 lbs. of explosive at 15" standoff was selected; while in bulging 3/4" thick 61S aluminum plate with a 4 lb. charge, the standoff was increased to 36". In order to minimize the rise in temperature due to adiabatic deformation, an increment loading technique was employed consisting of a succession of explosions (4 lb. charge at 15 inches standoff) until the desired strain level obtained or fracture occurred.

STRESS-STRAIN CONDITIONS IN BULGES OF HEAVY PLATE

The distribution of plastic strain in the bulge surface was deter-

mined by measuring the distortion of a 20-line-to-the inch grid applied
to the plate by the photogrid process. The measurement was made by
means of a microscope containing a crosshair and mounted on a micro-
meter slide. The micrometer-microscope in turn was mounted on a
platform supported by three adjustable legs (Figure 5). In the case of
elliptical bulges, the strains were measured in the convex surface a-
long lines parallel to the major and minor axes. The component par-
allel to the minor axis (the direction of major applied stress) was de-
signated e_1 and the component perpendicular to the minor axis, e_2.
A schematic of strain distribution has been used as a means of ready
reference and orientation for the reader. The schematic includes el-
ements scaled to represent grid distortion. Squares indicate equal ex-
tensions in all directions and rectangles indicate greater strain in one
direction than the other. In the case of the circular bulge, the conven-
tion was adopted of designating the component radial to the pole as e_1
and the circumferential component at any point on a radial line as e_2.
Measurement of the component of strain thru the thickness (e_3) was
made by micrometer caliper readings at regular intervals along the
major and minor axes of the ellipse or along radial lines in the cir-
cular bulge. The natural strain in the thickness direction was com-
puted from the expression $\log_e To/T$ where To and T are the original
and final thicknesses, respectively.

Since span-to-thickness ratio in bulge testing of sheet metals is
usually held at about 300:1 to assure membrane conditions and in bulg-

ing thick plate the ratio is only about 20:1, it is to be expected in the latter case that bending conditions prevail. A comparison of the strain states existing in the concave and convex surfaces of thick plate bulges confirmed the presence of bending. For example, in the early stages of elliptical bulging, measurement of e_1 in the concave surface indicated small compressive strains over the entire pole region. The e_2 component, on the other hand, consisted of small tensile strains in the pole region which were approximately 50% of the corresponding strain in the convex surface. See fig. (6) for a schematic representation of the strains in the concave and convex surfaces of circular and elliptical bulges at low levels of deformation.

As the result of bending, the sum of the biaxial surface components are not equal to the thickness strain (in the bulging of diaphrams constancy of volume in plastic flow requires that $e_1 + e_2 = e_3$). Figure (7) shows the relationship between thickness strain measured by micrometer caliper and the sum of the surface strains by photogrid. It is to be noted that at low levels of strain the sum of the surface strains increased much more rapidly than the thickness strain, whereas at higher levels of deformation their rates became more nearly equal. Using an arithmatical average of the strains in the concave and convex surfaces to provide a nominal value of bulge strain at any given section, (vector at midthickness - assuming a linear distribution of plastic flow) the sum of the average e_1 and e_2 strains may be plotted against the measured value of e_3. A reasonably good equality is indicated (fig. (7).

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DEVELOPMENT OF INSTABILITY

It has been pointed out that at a certain critical level of deformation a condition of instability may be expected to develop. When unstable flow occurs, straining becomes localized, the geometry of the test specimen changes, and the stress in that portion of the specimen undergoing plastic flow is no longer under control. For example, in the formation of an elliptical bulge, the strain ratio at the crown of the bulge changes continuously gradually approaching one. Thus, the limiting condition in an elliptical bulge is that stage of deformation at which there is an excessive alteration in the strain ratio; i.e., loss of control over the stress state. In the case of the circular bulge, the strain state is constant but instability is manifest by localization of flow and an attending loss of pole area (an important requirement of the weld bulge-test is that uniform deformation occur over an area sufficiently great to encompass weld deposit, heat-affected zone, and a portion of the unaffected parent plate).

Figure (8) illustrates schematically the distribution and progression of flow in a circular and elliptical bulge each formed by the same increment loading procedure (a succession of three 4 lb. shots at 12, 18 and 24 inch standoff). Note that in the case of the elliptical bulge, the rates of increase of e_1 and e_2 in the pole region were not equal, e_2 increased more rapidly than e_1; consequently, as straining progressed the strain state approached balanced biaxial tension. Localization of flow in the circular bulge resulted in a severe strain gradient. The marked difference in the progression of strain between the two

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geometries of bulge may be seen by noting that the increase in strain
was only 60% in the elliptical bulge as compared to 114% in the circular
bulge with the same increment loading. Localization of flow in the el-
liptical bulge was found to be best illustrated by thickness strain e_3.
The increase in e_3 from 1st to 2nd shot was quite uniform over most
of the bulge area; whereas the increase from 2nd to 3rd shot was large-
ly confined to the pole region - pointing to the formation of a secondary
bulge (fig. 7). Note also that in the plot of thickness strain versus
depth of bulge (fig. (3) the slope of the curve increased at a gradually
increasing rate up to about 10% reduction-in-thickness after which the
slope increased at a more rapid rate indicating that for a small increase
in depth of bulge, a large reduction in thickness occurred (analogous
to necking in the tensile test).

MODIFICATION OF STRAIN STATE DUE TO THE PRESENCE OF WELDS

The presence of a weld may greatly alter both the distribution and
progression of plastic flow in the bulge. In figure 9 the effects are
schematically illustrated for the case of an elliptical bulge containing
a weld of flow strength greatly overmatching that of the parent plate.
A comparison between the strain distributions in the weld and at pos-
itions somewhat removed from the weld disclosed that a marked re-
duction of strain (hereinafter called a strain deconcentration) occurr-
ed in the transweld direction at locations in the weld and near-weld
regions. In the initial stage of deformation the 1:2 strain state of the
unwelded bulge was modified to 1:1 by the transweld strain deconcen-

-10-

tration. Moreover, as strainingproceeded (from 1st to 2nd to 3rd shot) the magnitude of the transweld component was essentially un changed; whereas, the weld-longitudinal component increased until on the 3rd shot the strain was 2:1 - a complete reversal of the 1:2 strain ratio in the unwelded bulge.

Figure (10) illustrates the strain anisotropy of two welds of wide - ly different flow strengths in circular bulges of HTS. When the flow strength of the weld exceeded that of the base metal (E12016-HTS) a transweld strain deconcentration occurred in the weld and near-weld regions. When the flow strength of the weld was less than that of the base metal (E6010-HTS) a concentration of strain developed in the weld causing premature failure in the weld metal. The relatively low re- sistance to flow of the E6010 weld in HTS aggrevated the natural tend- ency for localization of flow in the circular bulge. A comparison of the distribution and progression of thickness strain in various comb- inations of weld and base metal flow strengths confirms this observ- ation. From figure 4, note that for a given increment of load (each shot consisting of 4 lbs. of explosive at 15" standoff) the flow strengths of weld and base metal determined the energy (number of shots) that could be delivered to the plate before instability developed. As a gen- eral "rule of thumb" 10% reduction of thickness in the pole region is the limit of useful strain in the explosion bulge test.

A COMPARISON OF CIRCULAR AND ELLIPTICAL TRANSITIONS

In order to provide a comparison between the fracture performance

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of circular and elliptical bulges, weldments were prepared using E6010 and E12016 weld metals and the same mild steel base metal as tested previously over the circular die (ref. 2). Two elliptical bulge transitions were determined for each weld metal - one with the weld on the major axis and one with the weld on the minor axis.

In the case of the E6010-MS combination (fig. 11) no difference was observed between the two orientations of weld in the elliptical bulge. The temperature corresponding to the lower side of the transition range was the same for circular and elliptical bulging. The upper transition, however, was approximately $25^{\circ}F$ higher using the elliptical die. The fractures initiated in the E6010 weld metal and generally propagated in the transweld direction. An occasional weld-longitudinal fracture occurred with the weld on the major axis.

The E12016-MS combination (fig. 12), on the other hand, indicated a decided difference between the two orientations of weld. With the weld on the major axis the transition range was broad, extending from approximately -110° to $-50^{\circ}F$ or higher. Fractures initiated in the base metal at distances of $\frac{1}{2}$" to $3\frac{1}{2}$ " from the centerline weld. With the weld on the minor axis a narrow transition was indicated at approximately $-80^{\circ}F$. Of nine fractures examined, four initiated at weld metal porosity and five initiated in the HAZ at a distance of approximately 3/4" from the weld centerline. Three of the four weld metal failures should be discounted in analyzing the effect of bulge geometry on transition because they were x-ray rejects (the weldments contain-

-12-

ing heavy porosity were tested at dry ice temperature to see whether HAZ failures would occur in spite of the porosity). A comparison between the transitions obtained by circular and elliptical bulging indicated the upper transition to be higher by the elliptical bulge. The difference between the circular and elliptical bulge was greatest with the weld on the major axis (approximately $50^{\circ}F$ higher by the elliptical bulge); with the weld on the minor axis, the strain state more nearly matched that of the circular bulge and the difference was only $25^{\circ}F$. Insufficient data are available for comment on the lower transition, although the indication is that with this orientation of weld there is no appreciable difference between the circular and elliptical bulge performance.

It appears that no particular advantage is gained by the use of the elliptical bulge. Anisotropy inherent to weldments results in unbalanced stress and strain in the weld and near-weld region of circular bulges. Thus, an unbalanced load imposed by means of elliptical geometry can accomplish little more than modify the unbalance introduced by the anisotropy of the weld region. The shift in the upper limit of the transition range is believed to be the result of this modification of the strain state. The lower limit, on the other hand, which corresponds to fracture at or about the elastic limit, would not be expected to be influenced by a modification of biaxial load field.

ACKNOWLEDGEMENTS

REFERENCES

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2. "Explosion Bulge Test Studies of the Deformation of Weldments" by C. E. Hartbower and W. S. Pellini THE WELDING JOURNAL Vol. 30(6) pg. 307-s to 318-s (June 1951).

3. "Investigation of Factors Which Determine the Performance of Weldments" by C. E. Hartbower and W. S. Pellini THE WELDING JOURNAL Vol. 30(10), pg. 499-s to 511-s (Oct. 1951).

4. "Hydraulic Bulge Testing of Sheet Metals" by W. T. Lankford ASTM Special Technical Publication #87 entitled SYMPOSIUM ON DEFORMATION OF METALS AS RELATED TO FORMING AND SERVICE (1948).

5. "Some Problems in Unstable Plastic Flow Under Biaxial Tension" by W. T. Lankford and E. Saibel AIME TRANS. Institute of Metals Division, Vol. 171, pg. 562 (1947).

FIGURE 1
EXPLOSION BULGE TEST EQUIPMENT
illustrates the simplicity of test procedures.

EXPLOSION BULGE TEST EQUIPMENT

FIGURE 1a
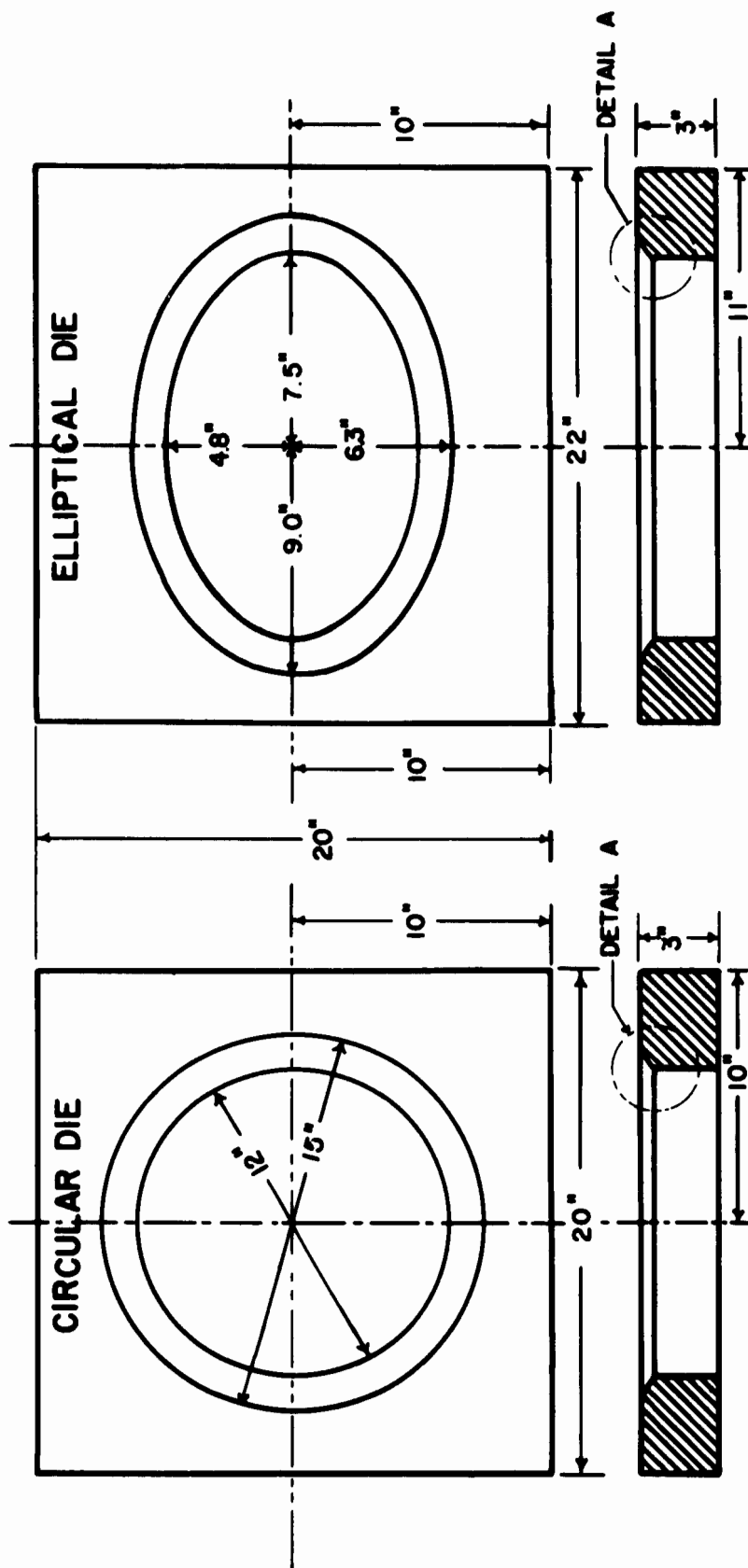**DETAILS OF THE DIES**

DETAIL A

ELLIPTICAL DIE
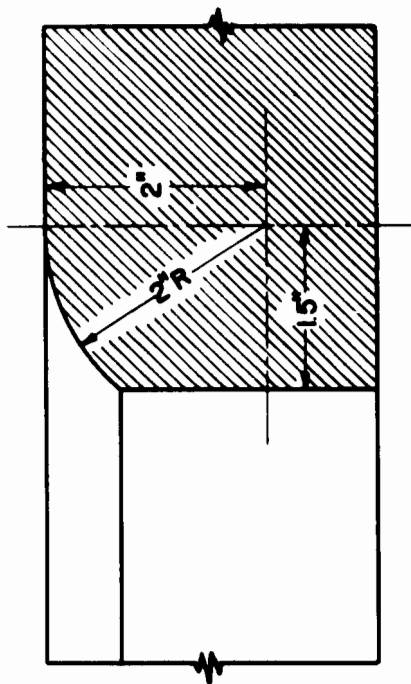
CIRCULAR DIE

FIGURE 2
CIRCULAR BULGE IN 3/4-INCH PLATE
three views of a single bulge show the effectiveness of
edge clamping by explosive action.

FIGURE 3
DEPTH OF BULGE
various relationships showing the reproducibility of
test results and criteria that may be used in evalua-
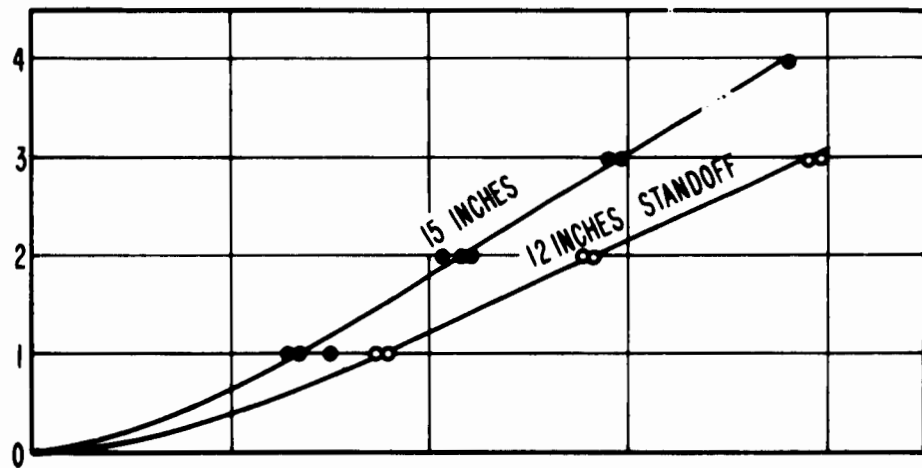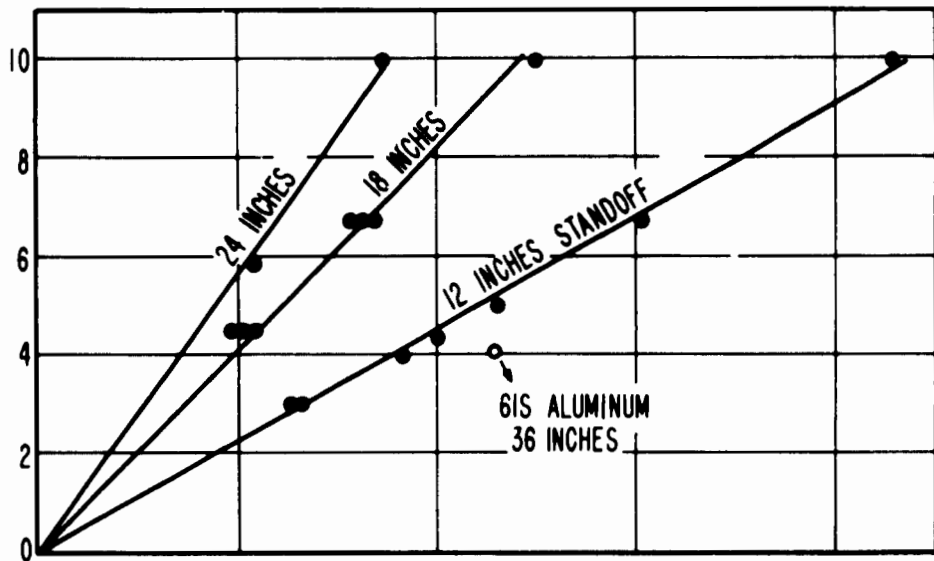ting performance.

DEPTH OF BULGE (INCHES)
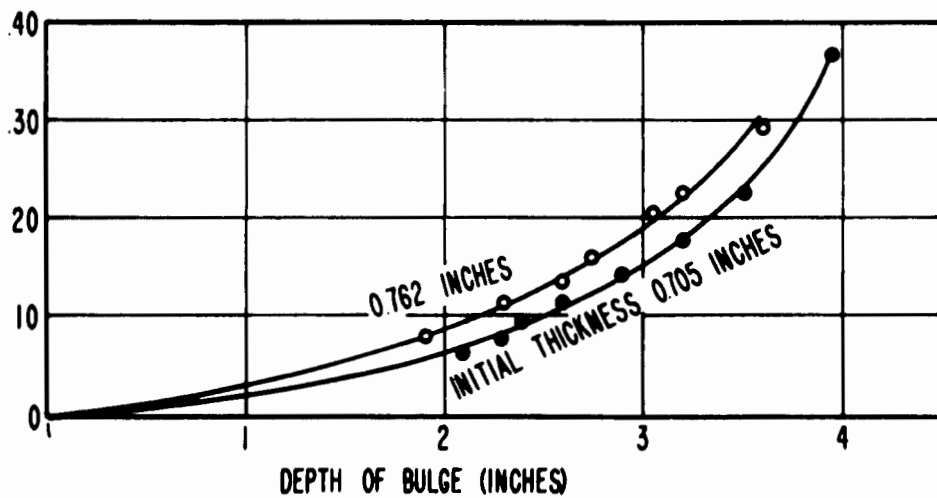
FIGURE 4
STRAIN DISTRIBUTIONS
the effect of weld and base metal flow strength in re-
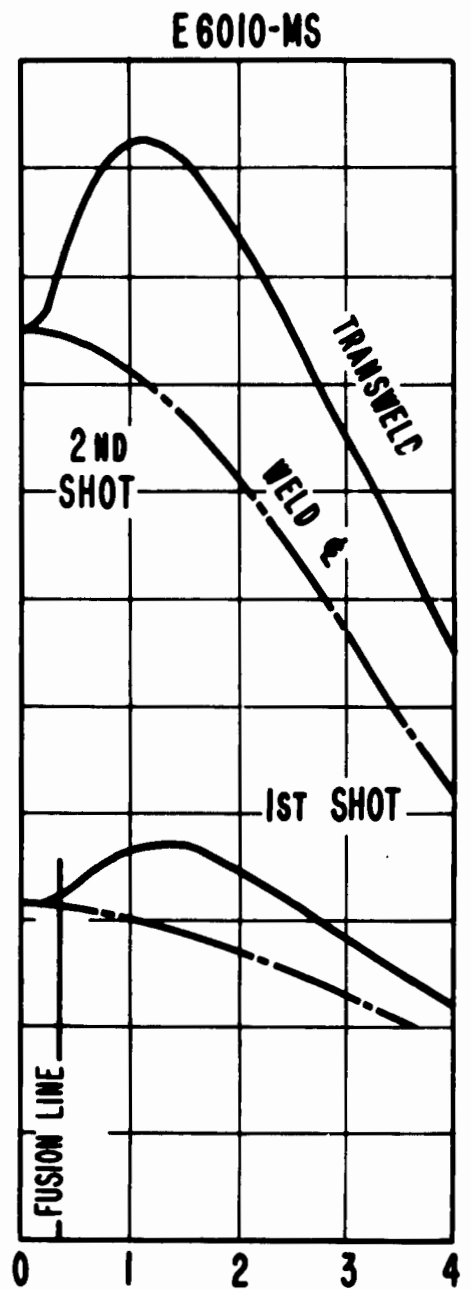straining plastic flow are indicated.

E 6010-MS

E 12016 – HTS

E 6010 – HTS

THICKNESS STRAIN (IN./IN.)

.140
.120
.100
.080
.060
.040
.020

3RD SHOT
TRANSWELD
WELD ℄
1ST SHOT
FUSION LINE

2ND SHOT
WELD ℄
TRANSWELD
1ST SHOT
FUSION LINE

2ND SHOT
TRANSWELD
WELD ℄
1ST SHOT
FUSION LINE

RADIAL DISTANCE (INCHES)

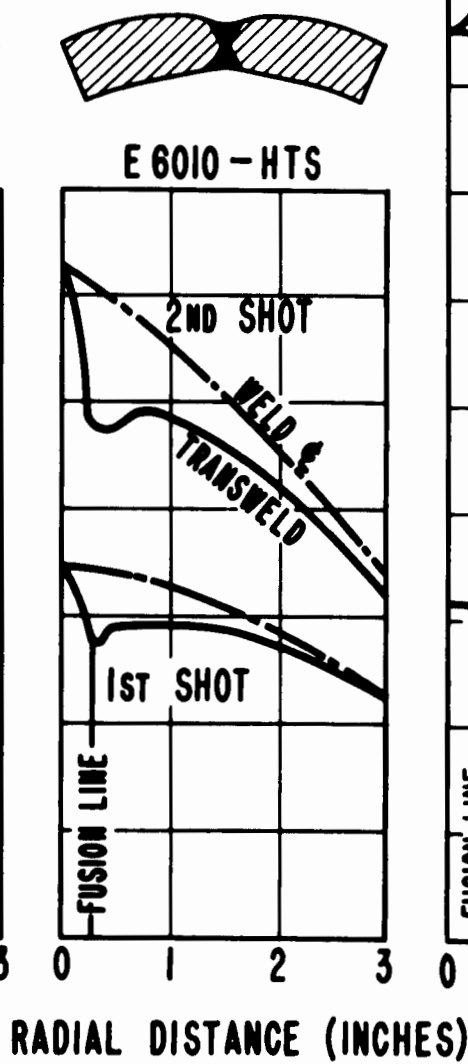0   1   2   3   0   1   2   3   0   1   2   3   4
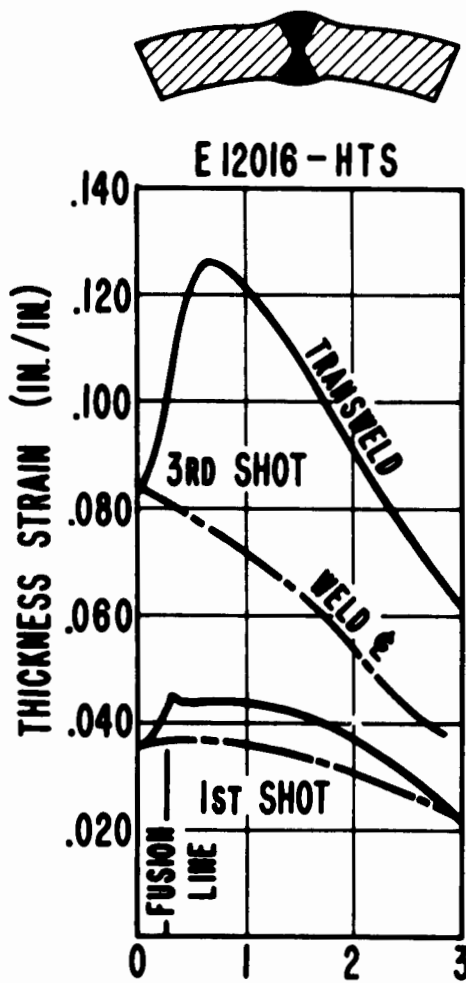
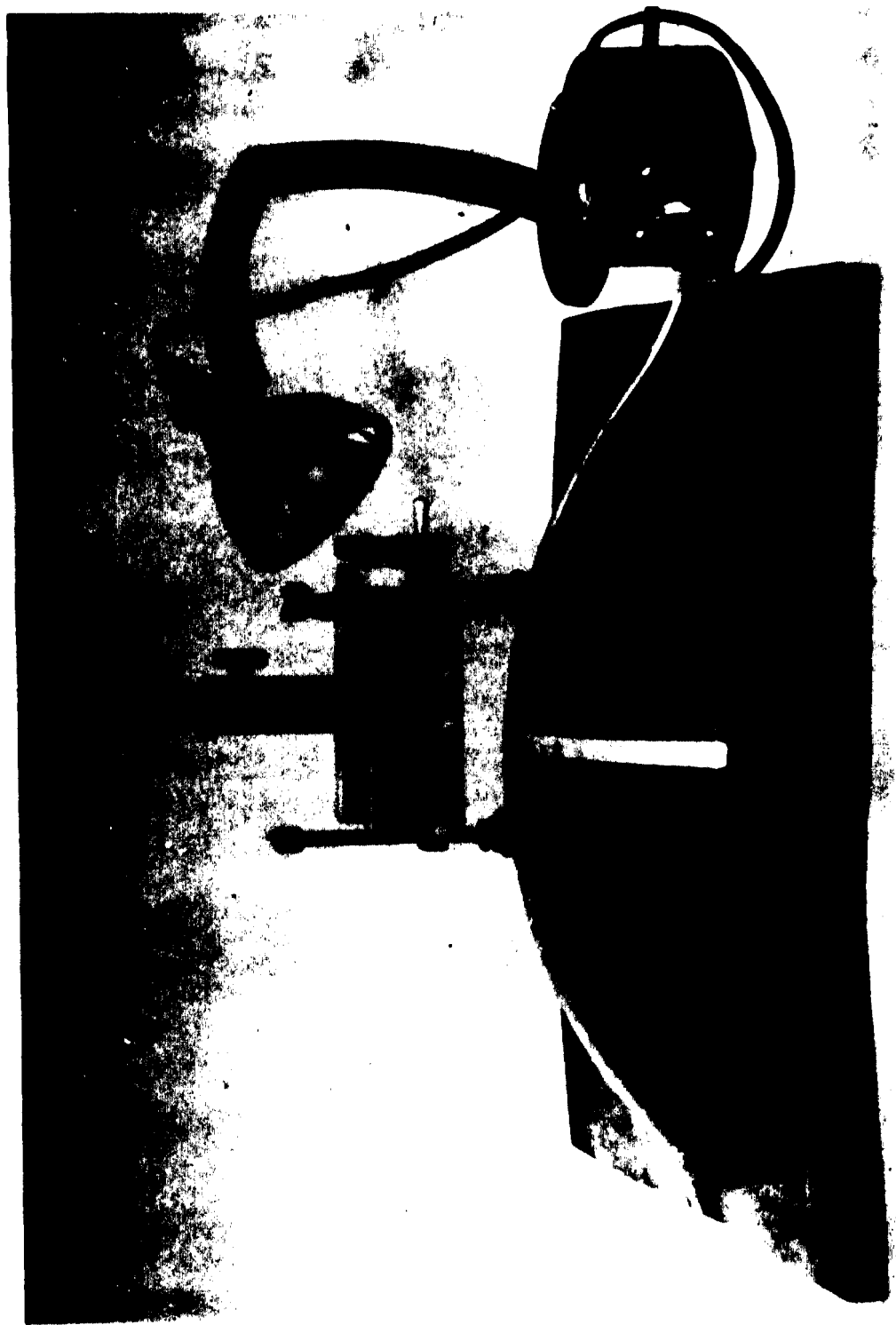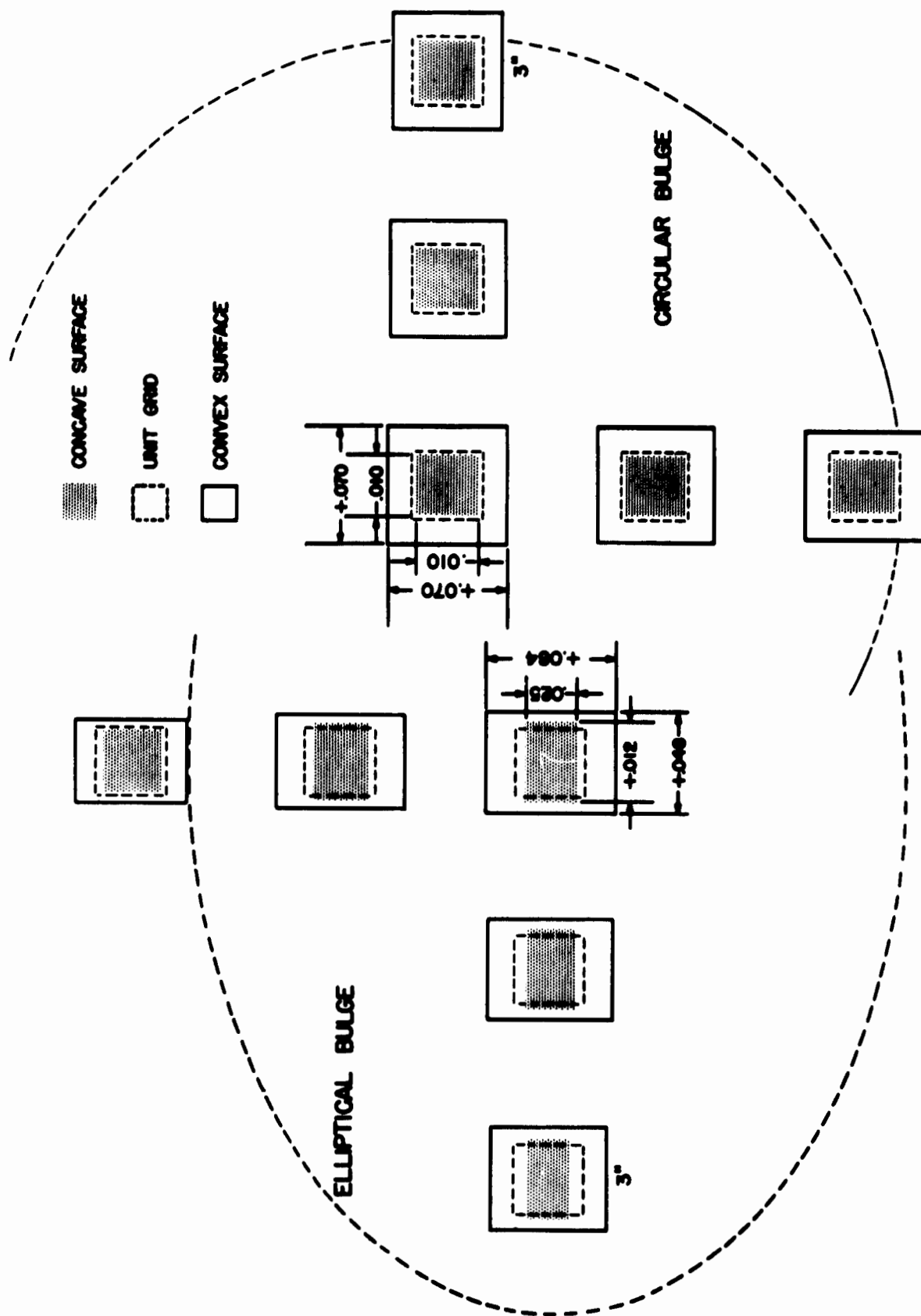**FIGURE 5**
MEASUREMENT OF SURFACE STRAIN

FIGURE 6
RELATIVE STRAINING IN THE CONCAVE AND CON-
VEX SURFACES
in the early stages of bulging the concave surface is in
compression.

RELATIVE STRAINING IN THE CONCAVE AND CONVEX SURFACES

FIGURE 7
**DISTRIBUTION OF THICKNESS STRAIN AND ITS
RELATION TO SURFACE STRAIN**
in the early stages of bulging, the strain in the convex
surface of the bulge develops much more rapidly than
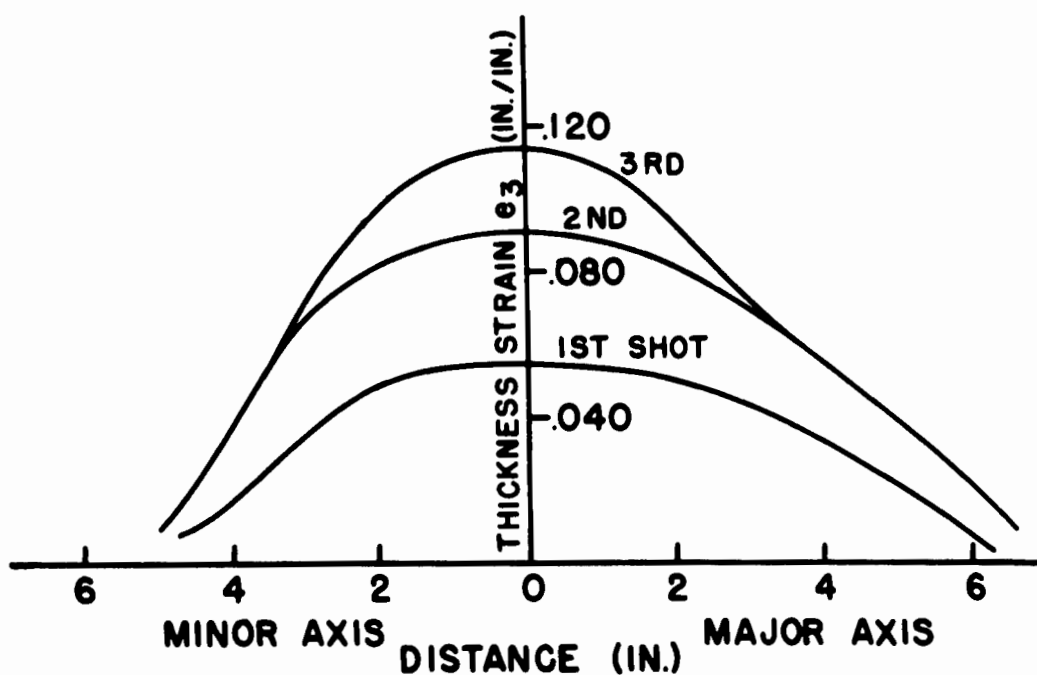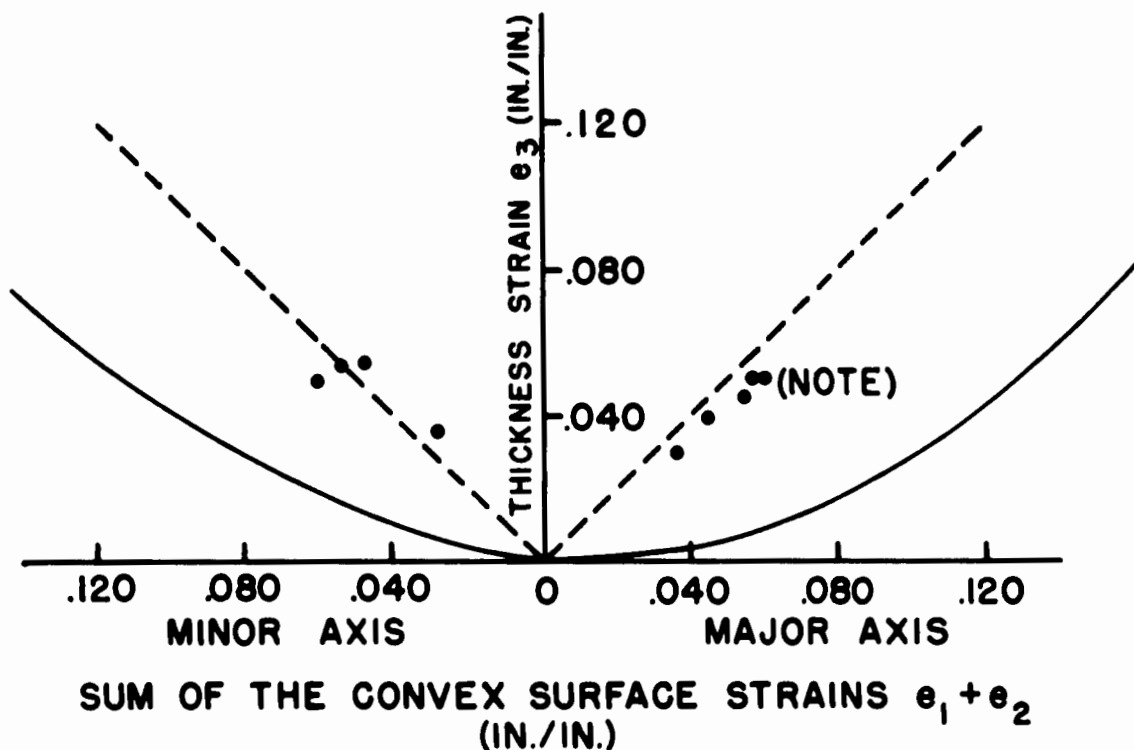the thickness strain.

SUM OF THE CONVEX SURFACE STRAINS $e_1 + e_2$
(IN./IN.)

NOTE: • REPRESENTS A PLOT OF THE SUM OF THE
ARITHMATICAL AVERAGES OF THE STRAINS IN THE
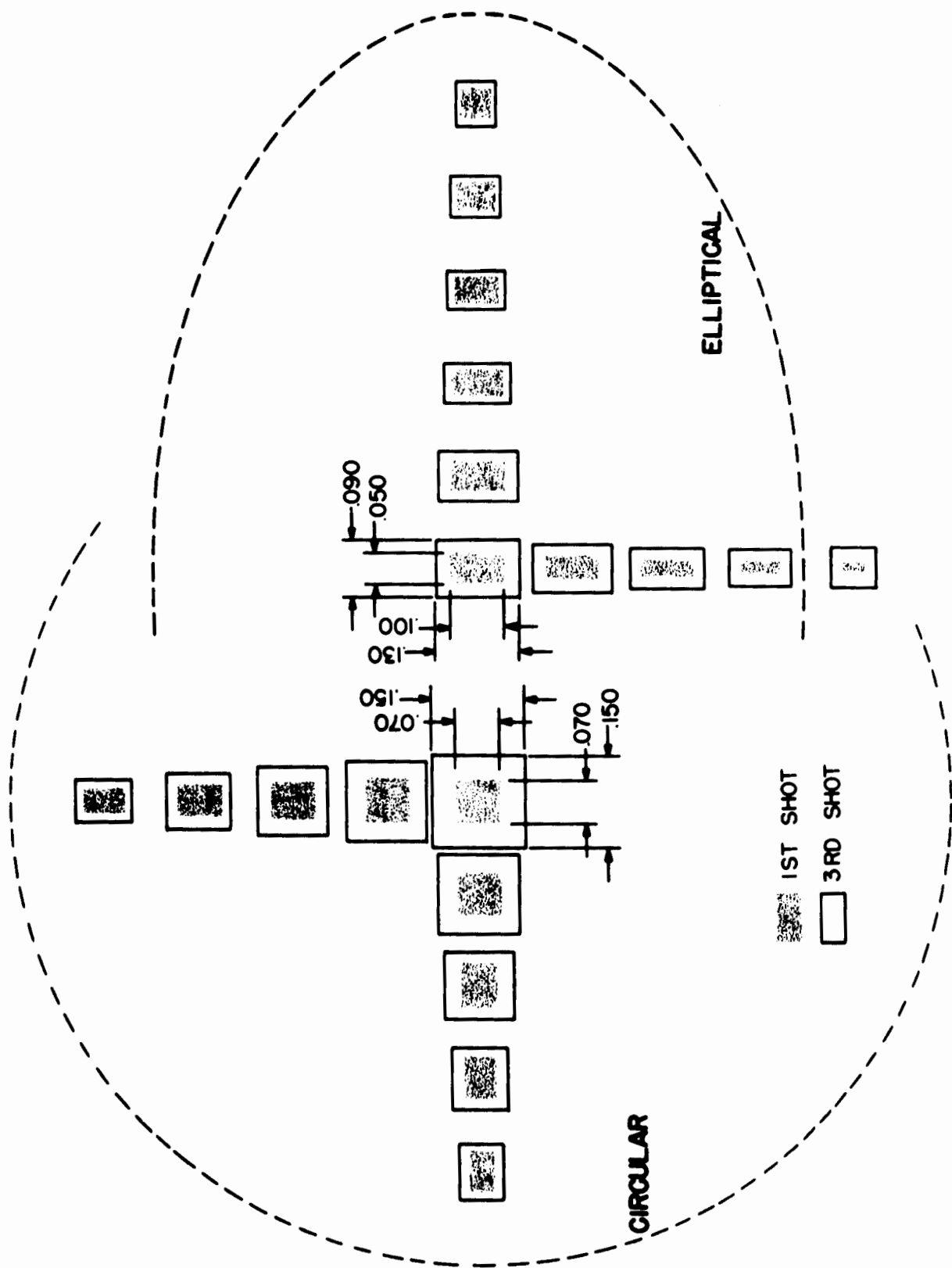CONCAVE AND CONVEX SURFACES VS. THE
MEASURED VALUE OF e_3

FIGURE 8
DISTRIBUTION AND PROGRESSION OF SURFACE
STRAIN ON REPEATED LOADING
instability and localization of flow are indicated.

.090
.050
.100
.130
.150
.070
.070
.150

1ST SHOT
3RD SHOT

ELLIPTICAL

CIRCULAR

DISTRIBUTION AND PROGRESSION OF SURFACE STRAIN ON REPEATED LOADING

FIGURE 9
**EFFECT OF WELDING ON THE DISTRIBUTION AND
PROGRESSION OF PLASTIC FLOW**
comparing welded and unwelded, note the marked de-
concentration of transweld strain and the equality of
strain in the weld-longitudinal direction; comparing
1st and 3rd shots welded, note the resistance of the
weld metal to flow in the transweld direction.

WELDED

UNWELDED

MAJOR AXIS

WELD

MINOR AXIS

EFFECT OF WELDING ON THE DISTRIBUTION OF PLASTIC FLOW

1ST SHOT

3RD SHOT

MAJOR AXIS

WELD

MINOR AXIS

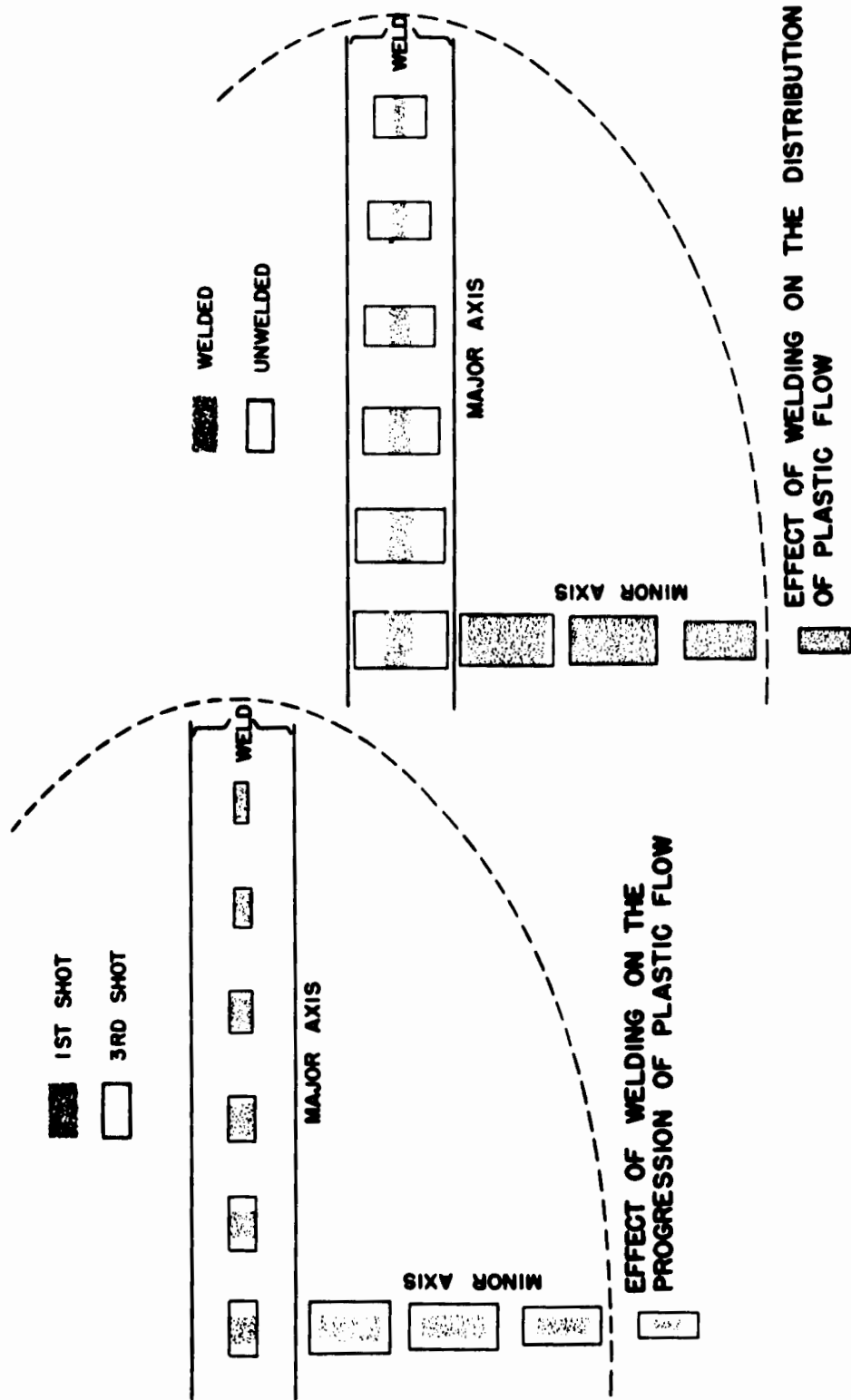EFFECT OF WELDING ON THE PROGRESSION OF PLASTIC FLOW

FIGURE 10
DISTRIBUTION OF STRAIN IN WELDS OF DIFFERENT
FLOW STRENGTHS
with the flow strength of weld metal greater than that
of the base metal, a strain deconcentration develops in
the transweld direction; with weld flow strength less
than that of the base metal, a strain concentration oc-
curs in the joint.

E6010—HTS
WELD

.060
.100

.065
.120

3"

E12016—HTS
WELD

.060
.060

.025
.040

3"

1ST SHOT

2ND SHOT

FIGURE 11
**TRANSITIONS FROM DUCTILE TO BRITTLE BE-
HAVIOR IN CIRCULAR VERSUS ELLIPTICAL
BULGES -- E6010 WELD METAL IN MILD STEEL**
little or no difference is indicated between the two
geometries of bulge at the temperature producing
extreme brittleness (failure at a near-zero level
of strain).

EXPLOSION BULGE TRANSITIONS
FOR MILD STEEL WELDMENTS
E6010 WELD

CIRCULAR
E6010 WELD
FINISH MACHINED TO 0.650 IN.

THICKNESS STRAIN (IN./IN.) I 1/2 IN. FROM WELD

TESTING TEMPERATURE °F

E6010 MILD STEEL
$\overset{\times}{\circ}$ — WELD ON MINOR AXIS
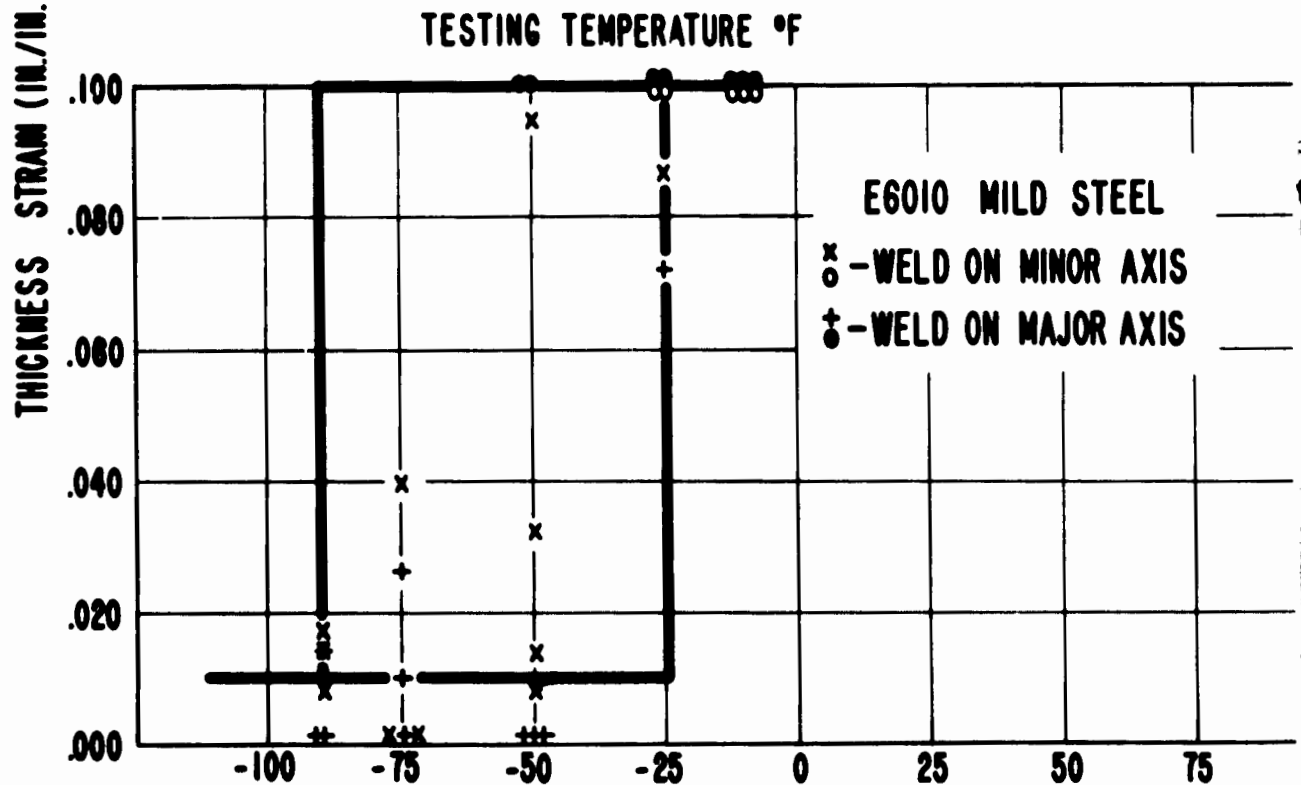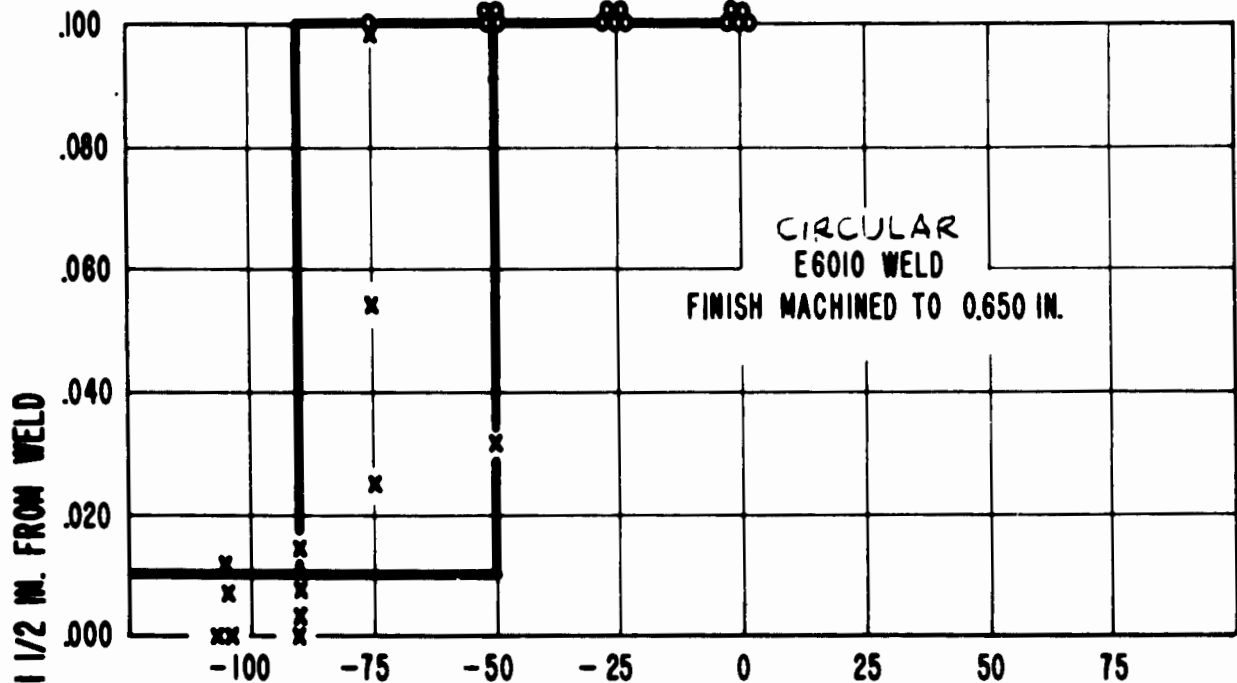$\overset{+}{\bullet}$ — WELD ON MAJOR AXIS

FIGURE 12
TRANSITIONS FROM DUCTILE TO BRITTLE BE-
HAVIOR IN CIRCULAR VERSUS ELLIPTICAL
BULGES -- E12016 WELD METAL IN MILD STEEL
note the difference in performance between the two
orientations of weld in the elliptical bulge.

EXPLOSION BULGE TRANSITIONS
FOR MILD STEEL WELDMENTS

CIRCULAR
E12016 WELD
FINISH MACHINED TO 0.650 IN.

TESTING TEMPERATURE °F

THICKNESS STRAIN (IN./IN.) 1 1/2 IN. FROM WELD

E12016 MILD STEEL
x/o – WELD ON MINOR AXIS
+/• – WELD ON MAJOR AXIS